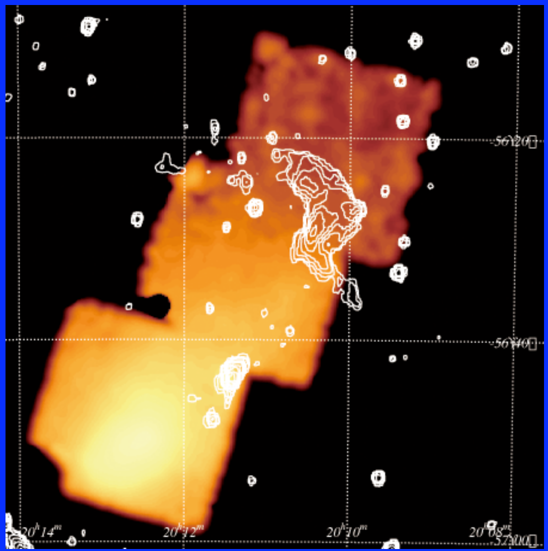
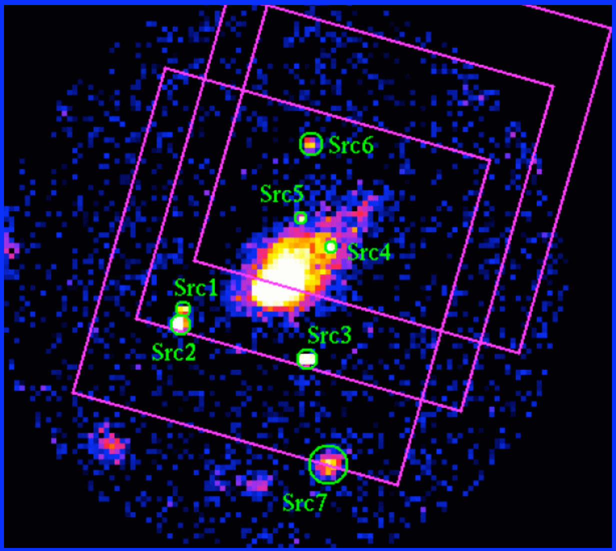
Hard X-rays from Clusters: Suzaku and XMM-Newton Observations of Coma, Abell 3667, and Ophiuchus



A3667 XIS images and radio contours

Craig Sarazin
University of Virginia



A3667 PIN FOVs on Rosat Image

Collaborators

Kazuhiro Nakazawa (Univ. Tokyo) – Abell 3667

Daniel R. Wik (Univ. Virginia) - Coma

Yutaka Fujita (Osaka Univ.) - Ophiuchus

Alexis Finoguenov (MPE, Univ. Maryland Balt. County) – XMM-Newton

Yasushi Fukazawa, Naomi Kawano (Hiroshima Univ.)

Kiyoshi Hayashida, Masaaki Nagai (Osaka Univ.)

Susumu Inoue (NAOJ), Madoka Kawaharada (RIKEN),

Takao Kitaguchi, Kazuo Makishima, Sho Okuyama (U. Tokyo)

Hironori Matsumoto (Kyoto Univ.),

Nobuhiro Okabe (Tohoku Univ.), Thomas Reiprich (Bonn Univ.)

Motokazu Takizawa (Yamagata Univ.)

Tracy E. Clarke (NRL, Interferometrics)

Cluster Radio Relics and Halos

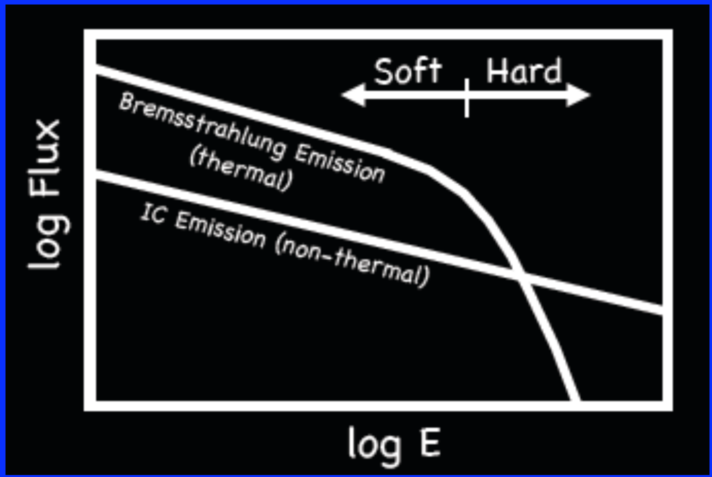
- Diffuse, cluster-scale radio emission
- No associated radio galaxy
- Steep radio spectra
- Only in merging clusters
- Cluster radio halos: central and symmetric
  - Due to turbulent acceleration behind shocks (?)
- Cluster radio relics: peripheral and elongated
  - Due to merger shock (re)acceleration (?)
- Should also emit hard X-rays by Inverse Compton scattering of CMB

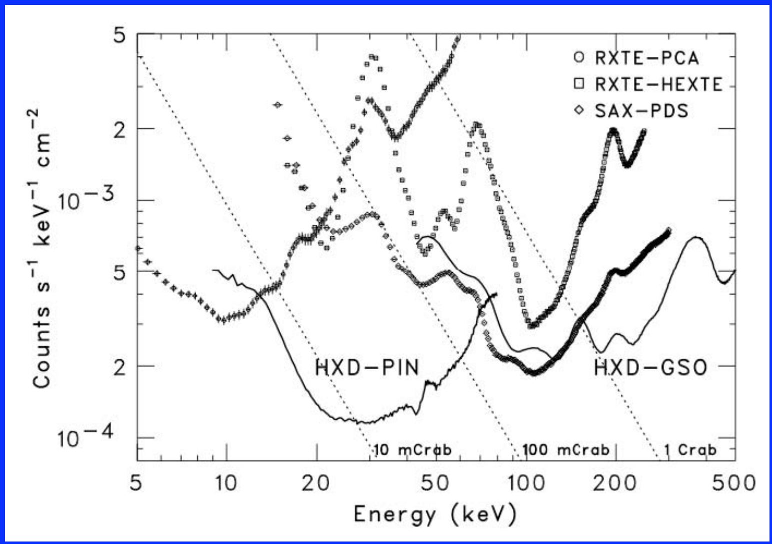
Measuring or Limiting the Magnetic Field

- Measure both IC X-rays and synchrotron radio → determine or limit energy of relativistic electrons and magnetic field
  - Radio ∝ (energy in relativistic electrons) x (magnetic energy density)
  - IC ∝ (energy in relativistic electrons) x (CMB energy density)
- Detect both → E (rel. e) & B
- Upper limit on IC → upper limit on E (rel. e).
  → lower limit on B

Suzaku HXD PIN

- Suzaku's Hard X-ray Detector (HXD) is ~3x more sensitive
- Significantly lower background (20-50 keV)
- Narrower FOV (34' HPD) → avoid AGN





Suzaku Observations

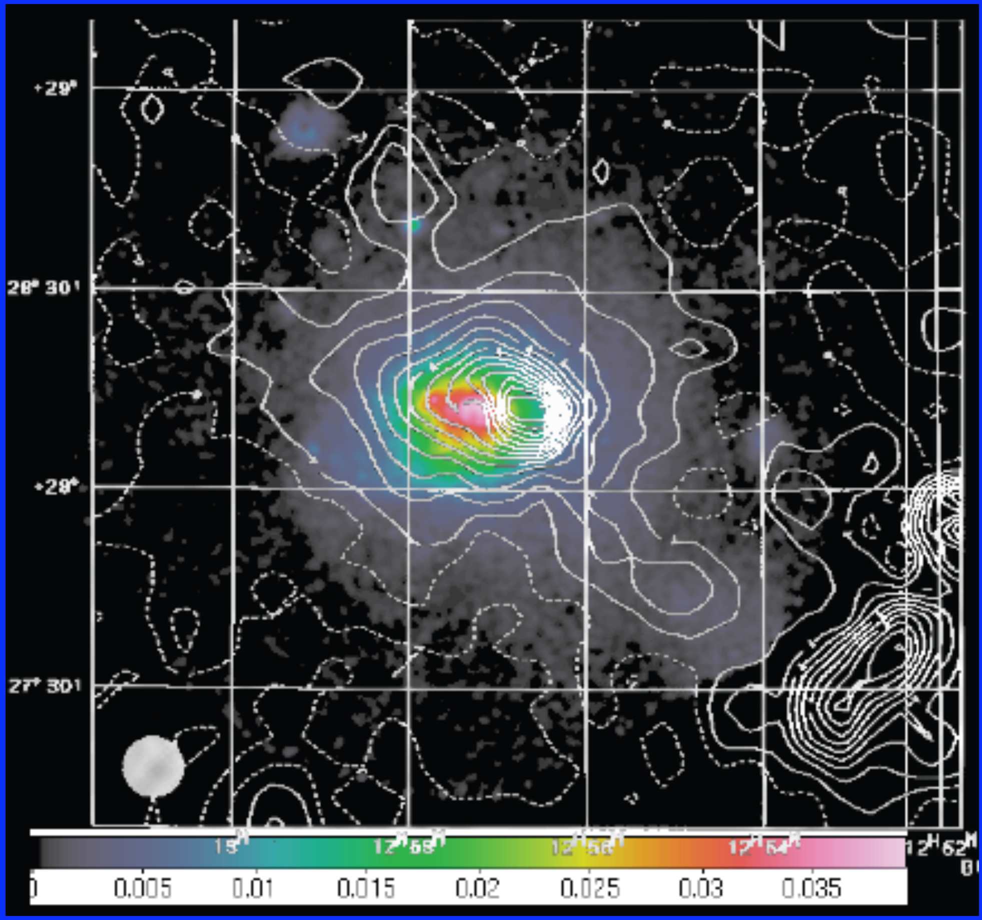
- Coma cluster – brightest radio halo
- Abell 3667 – brightest radio relic
- Ophiuchus – hottest nearby cluster

Coma Cluster

Coma is the brightest non-cooling core cluster and hosts the brightest radio halo

Color: X-ray ROSAT

Contours: Radio (Deiss et al. 1997)



Coma Cluster – IC Hard X-rays?

- Long history of searches
- Recent claimed detections
  - BeppoSAX: $F_X = 1.5 \times 10^{-11}$ ergs/cm^2/s, 20-80 keV
    (Fusco-Femiano et al. 2004, 2007)
  - RXTE: $F_X = 1.6 \times 10^{-11}$ ergs/cm^2/s, 20-80 keV
    (Rephaeli & Gruber 2002)
- But, very controversial
  - BeppoSAX: $F_X < 8.1 \times 10^{-12}$ ergs/cm^2/s, 20-80 keV
    (Rossetti & Molendi 2004, 2007)
  - INTEGRAL: hard X-rays purely thermal
    (Renaud et al. 2006, Eckert et al. 2007)
  - INTEGRAL/RXTE/ROSAT: hard X-rays purely thermal
    (Lutovinov et al. 2008)

Suzaku Observation of Coma

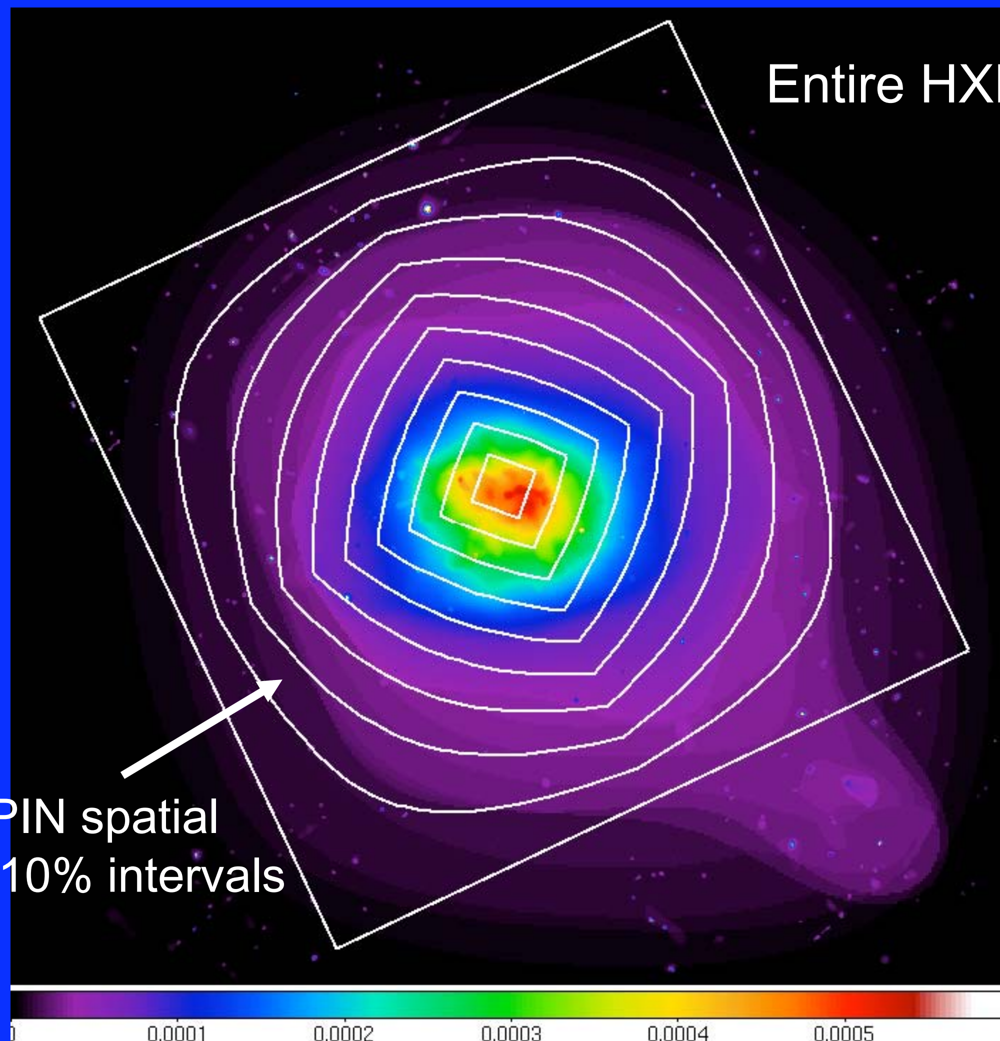
- 156 ksec (PIN), 31 May – 4 June 2006
- NXB model agrees well with Earth-blocked flux and spectrum
- Model CXB
- Model AGN point srcs (small effect)
- Joint fit with XMM/Newton and/or Suzaku XIS to model thermal emission – key!

Joint XMM - PIN Analysis

To ‘’PIN’’ down the thermal emission . . .

- Mosaic of XMM/Newton exposures to cover cluster (Schuecker et al. 2004; Finoguenov in this work)
- Extract XMM spectra in regions of ~constant PIN area

Entire HXD FOV



Contours of PIN spatial sensitivity in 10% intervals

XMM 2-7.5 keV image, Schuecker et al. 2004

Joint XMM - PIN Analysis

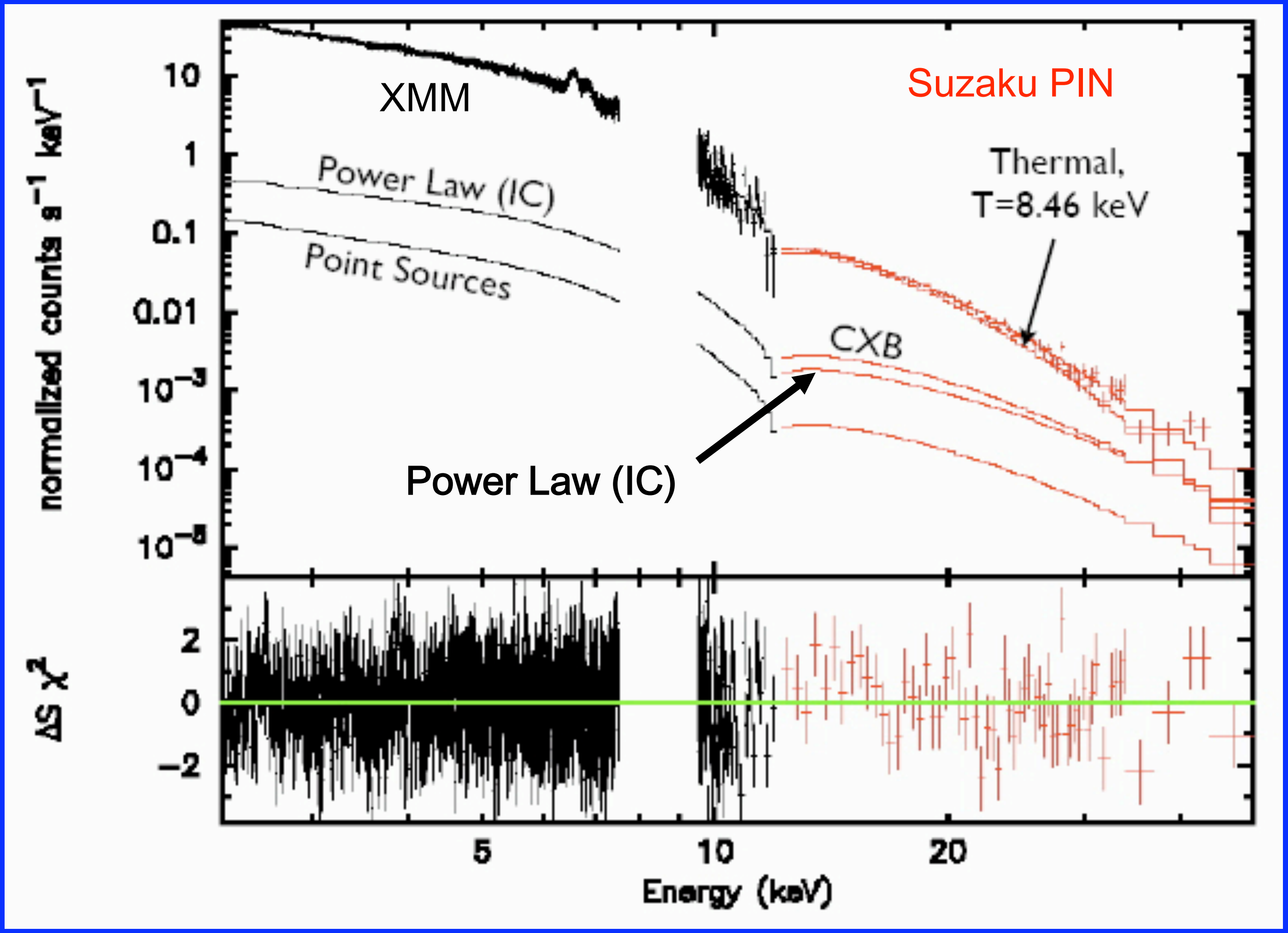
To "PIN" down the thermal emission . . .

- Mosaic of XMM/Newton exposures to cover cluster (Schuecker et al. 2004; Finoguenov in this work)
- Extract XMM spectra in regions of ~constant PIN area
- Weight by PIN area, combine
- Gives thermal spectrum as seen by PIN, correct shape and flux
- Fit PIN and XMM jointly

Coma: Spectral Fitting Results

- Single temperature model with no second component not a very good fit → hard X-ray excess
- Addition of power-law improves fit

Best-fit Single Temperature plus Power Law



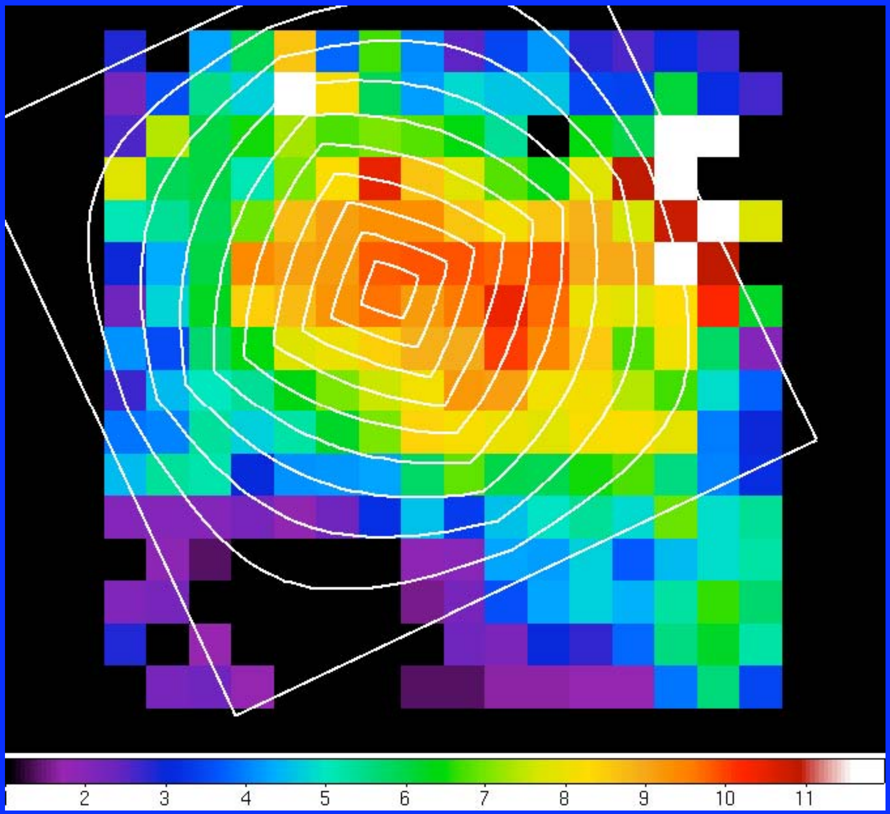
Coma: Spectral Fitting Results

- Single temperature model with no second component not a very good fit → hard X-ray excess
- Addition of power-law improves fit, but
  - Best-fit $\Gamma = 1.46$ flatter than radio spectrum
- Two-temperature model better than one temperature + power-law

Hard excess due to thermal structure in gas?

Multi-Temperature Model

- XMM-Newton mosaic used to construct temperature map
- Combine models for regions weighted by PIN effective area
- Provides good fit to data with no adjustment of models or normalization

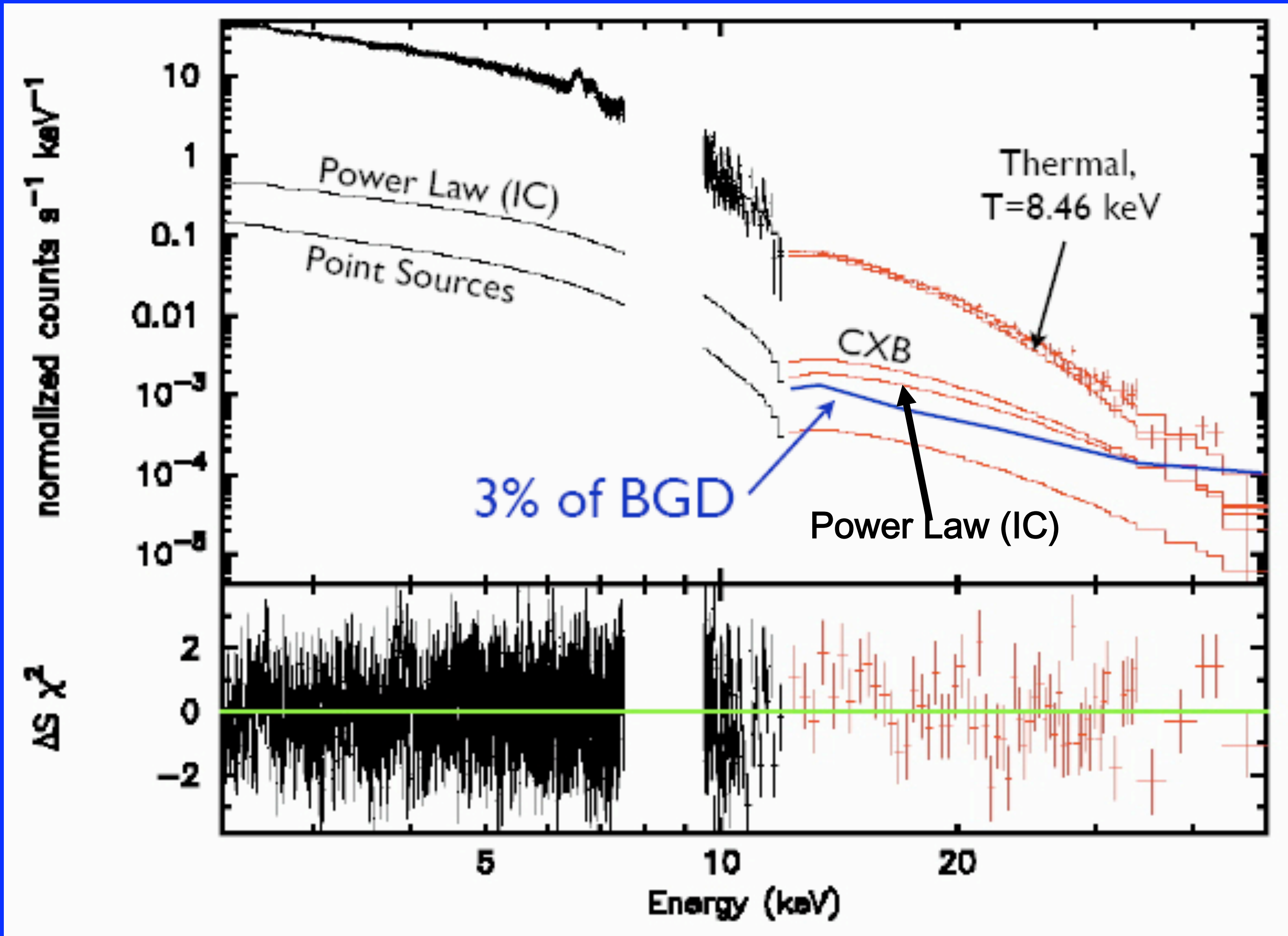


Hard excess probably thermal

Coma: Spectral Fitting Results (Cont.)

Doesn't include systematic errors

- NXB (non-X-ray background) 3%
- CXB
- XMM/Suzaku cross-calibration



normalized counts s^{-1} keV^{-1}
10
1
0.1
0.01
10^{-3}
10^{-4}
10^{-5}
Power Law (IC)
Point Sources
Thermal,
T=8.46 keV
CXB
3% of BGD
Power Law (IC)
$\Delta S\ \chi^2$
2
0
−2
5
10
20
Energy (keV)

Coma: Spectral Fitting Results (Cont.)

Doesn't include systematic errors

- NXB (non-X-ray background) 3%
- CXB
- XMM/Suzaku cross-calibration

• Take 90% errors, combine

Power-law not required

Upper Limit on IC

- For $\Gamma = 2.0$ (from radio)
  F_X(20-80 keV) < 7.8×10^{-12} ergs/cm^2/s
  (90% confidence),
- Factor of 2 below
  - BeppoSAX (Fusco-Femiano et al. 2004) and
  - RXTE (Rephaeli & Gruber 2002) detections
  - These detections inconsistent for any sensible Γ
- Lower limit $B > 0.15$ μG
  - Consistent with B_{eq}~0.5 μG (Giovannini et al. 1993)

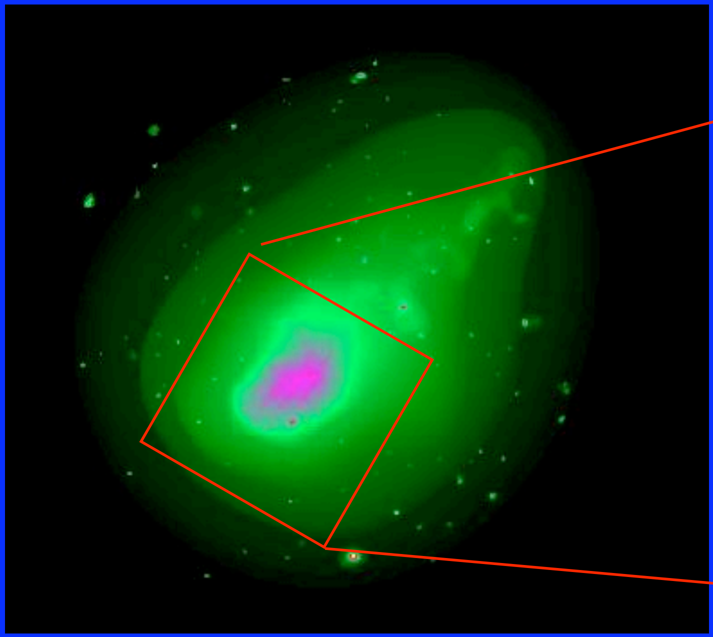
Coma: Spectral Fitting Results

Thermal interpretation of hard spectrum agrees with

- INTEGRAL results (Renaud et al. 2006, Eckert et al. 2007)
- Broadband study INTEGRAL/RXTE/ ROSAT (Lutovinov et al. 2008)

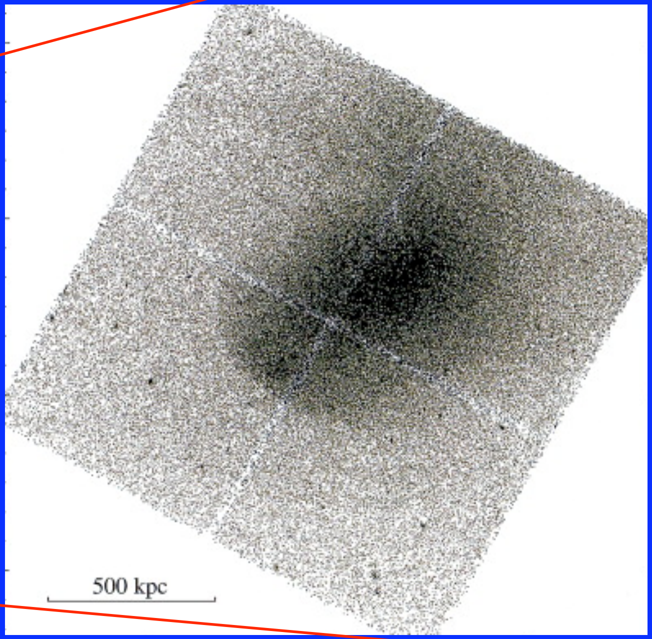
Abell 3667 – Merging Cluster

XMM



Briel et al. 2004; this work

Chandra



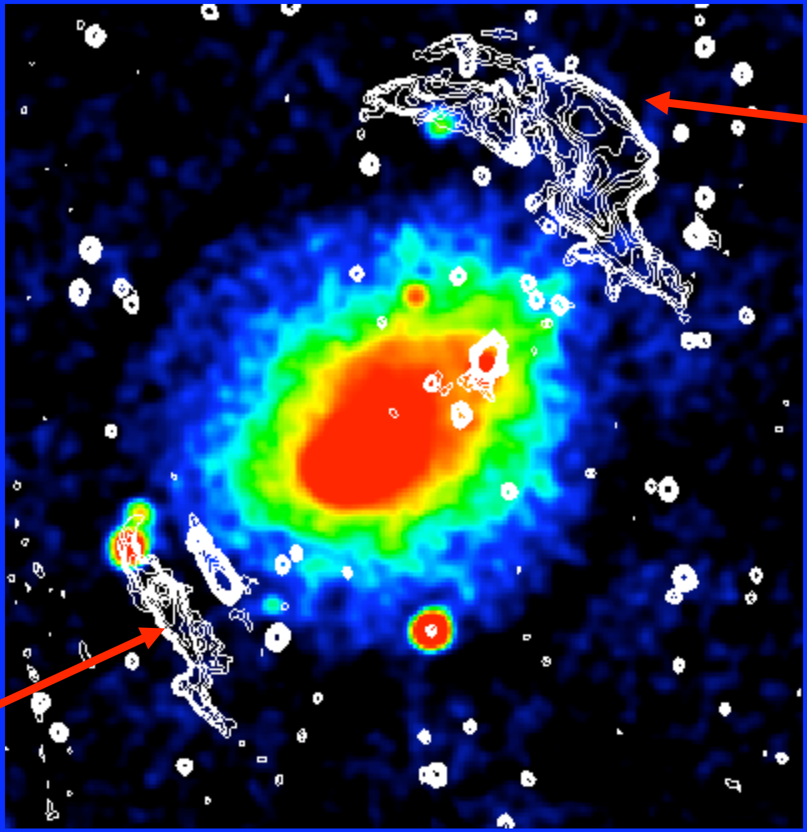
Vikhlinin et al. 2000

- Major merger along NW-SE axis
- z = 0.0552

- Cold front, remnant of cool core of one subcluster

Double Radio Relics

ROSAT (color), radio contours



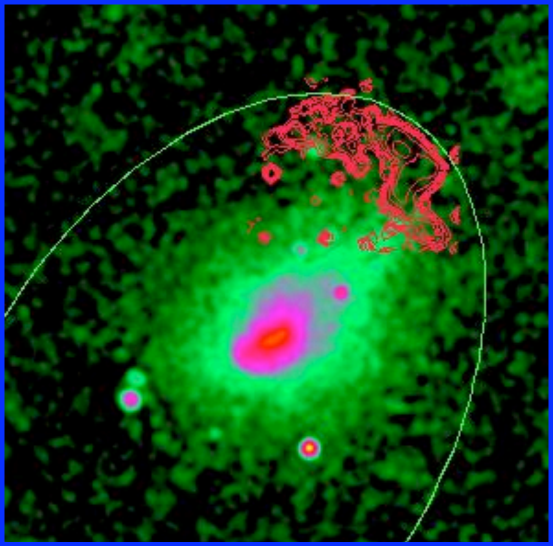
NW Radio Relic

SE Radio Relic

Röttgering et al. 1997

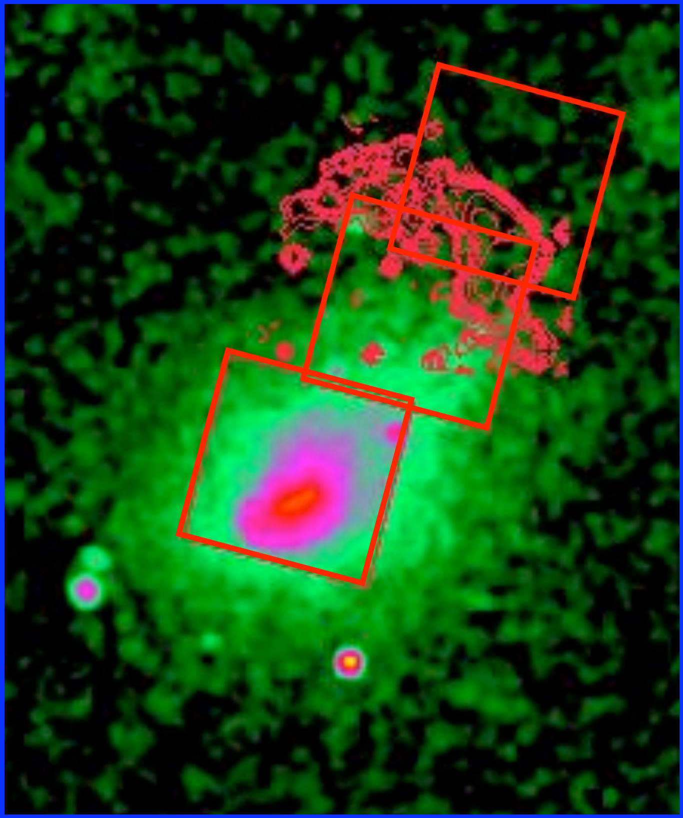
NW Radio Relic in Abell 3667

- Brightest diffuse cluster source
  3.7 Jy at 20 cm (Johnston-Hollitt 2004)
- Located at large projected radius ~2.2 Mpc → expect weak B field
- Should be a very strong IC HXR source!
- Steep radio spectra, α =1.1
  Γ = 2.1 at 20 cm
- Sharp outer edge, flatter spectrum,
  B parallel to outer edge
- Merger Shock at outer edge !?

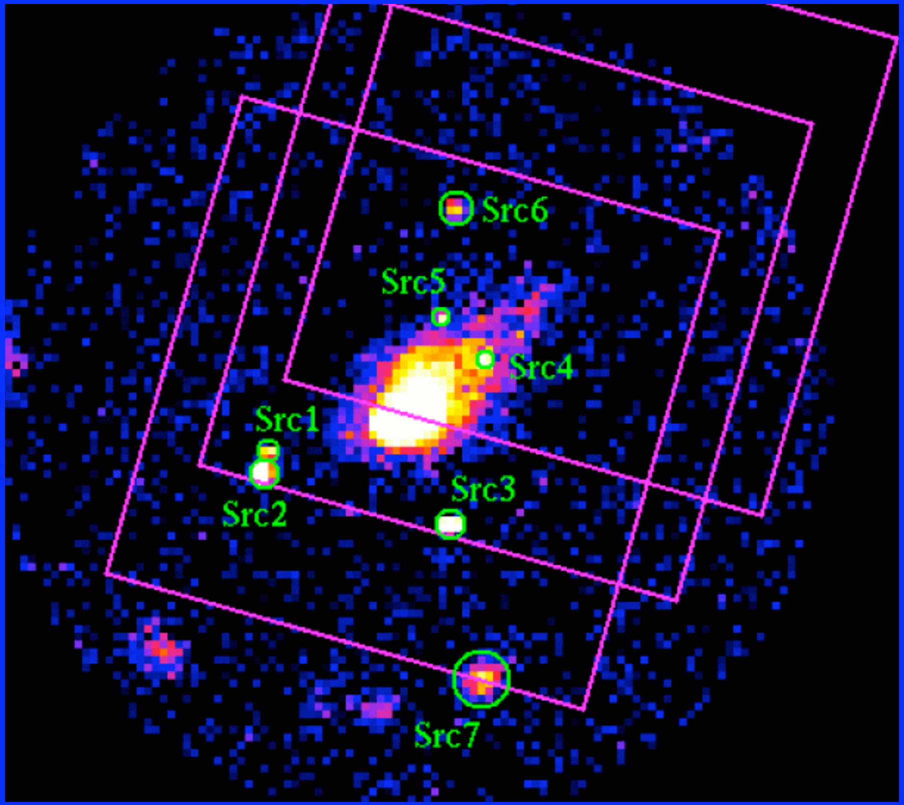


Sarazin et al. 2007

3 Suzaku Observations



XIS FOVs

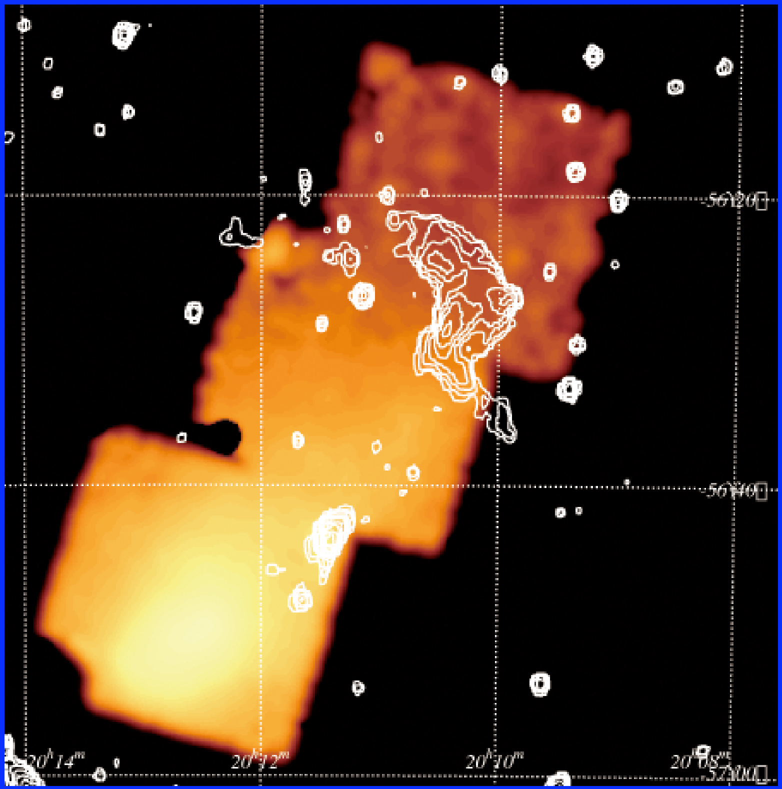


HXD/PIN FOVs

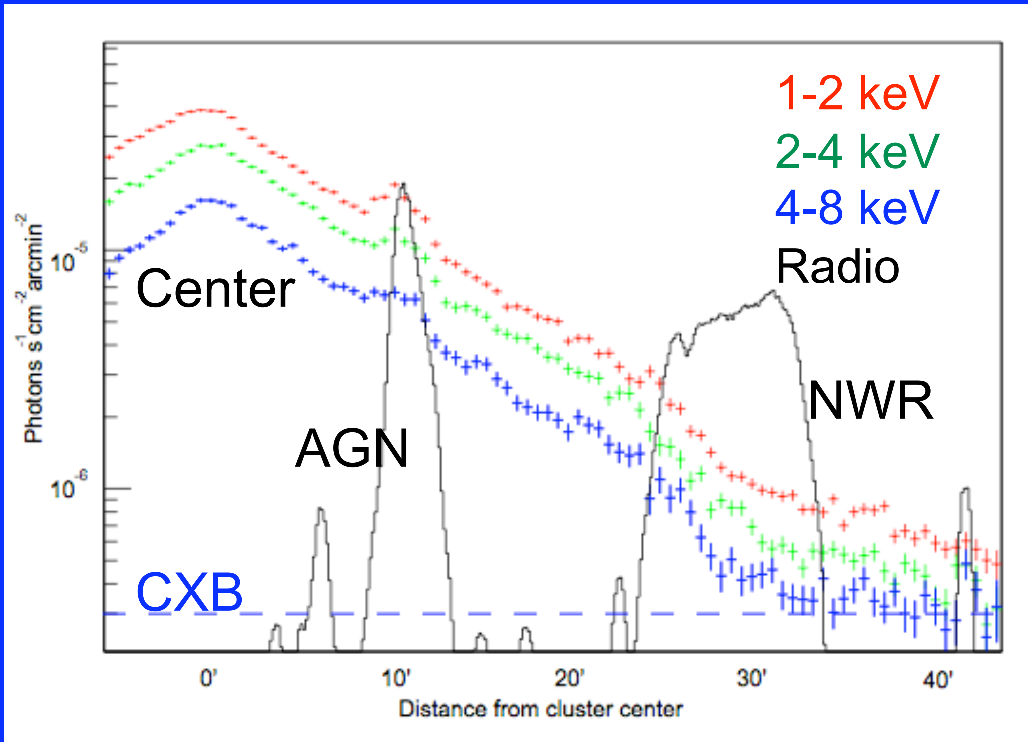
- 3 observations, 3-7 May 2006
- Exposures of ~20, ~17, ~78 ksec

Intracluster Gas at Large Radii

XIS 1-4 keV image



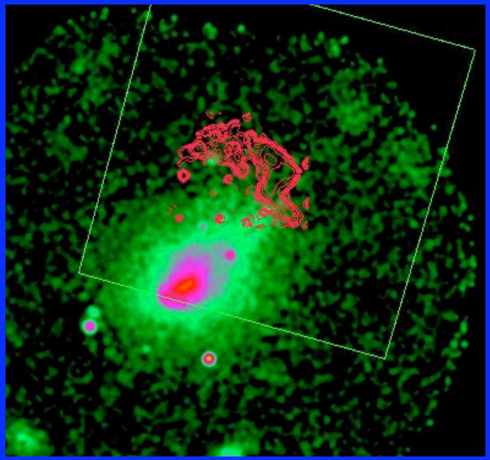
XIS and Radio Surface Brightness

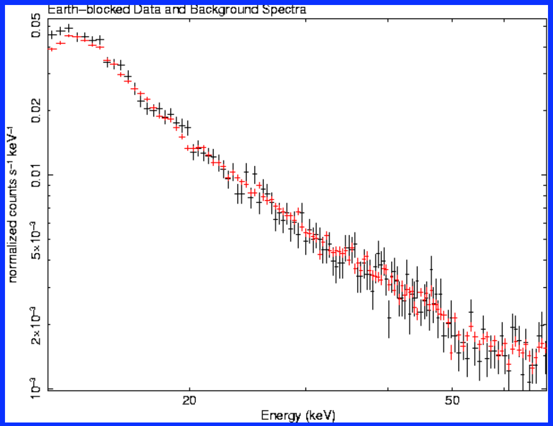


Hot gas out to ≈ 42 arcmin = 2.6 Mpc ≈ virial radius (but, along merger axis of merging cluster?)

HXD/PIN Observation of NW Radio Relic

- 73.5 ksec exposure in PIN
- NXB model agrees well with Earth-blocked flux (2.1%) and spectrum
- Model CXB
- Model AGN point srcs
- Relic at large projected radius → thermal emission weak but still very important
- Model thermal based on XIS and/or XMM

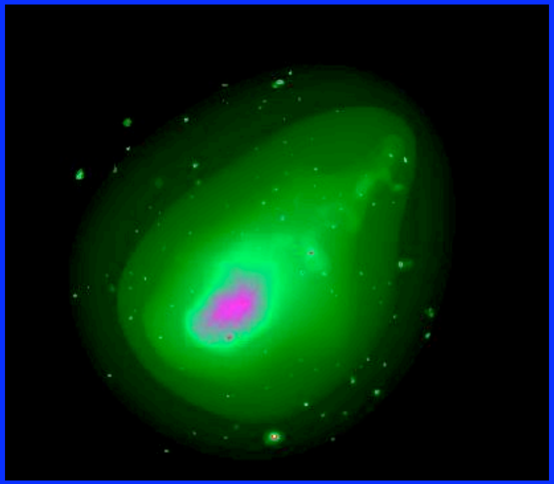




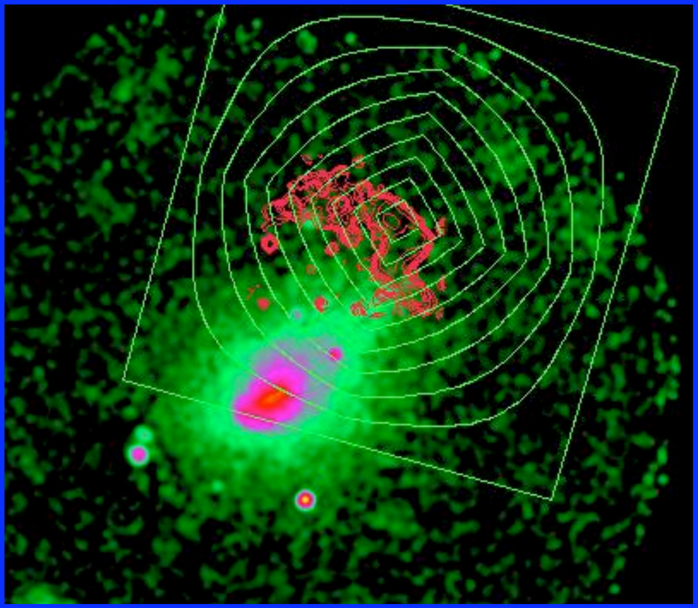
Earth-blocked data vs. NXB model

Joint XMM - PIN Analysis

- Mosaic of XMM/Newton exposures to cover cluster (Briel et al. 2004; this work)
- Extract XMM spectra in regions of ~constant PIN area
- Weight by PIN area, combine
- Gives thermal spectrum as seen by PIN, correct shape and flux
- Fit PIN and XMM jointly

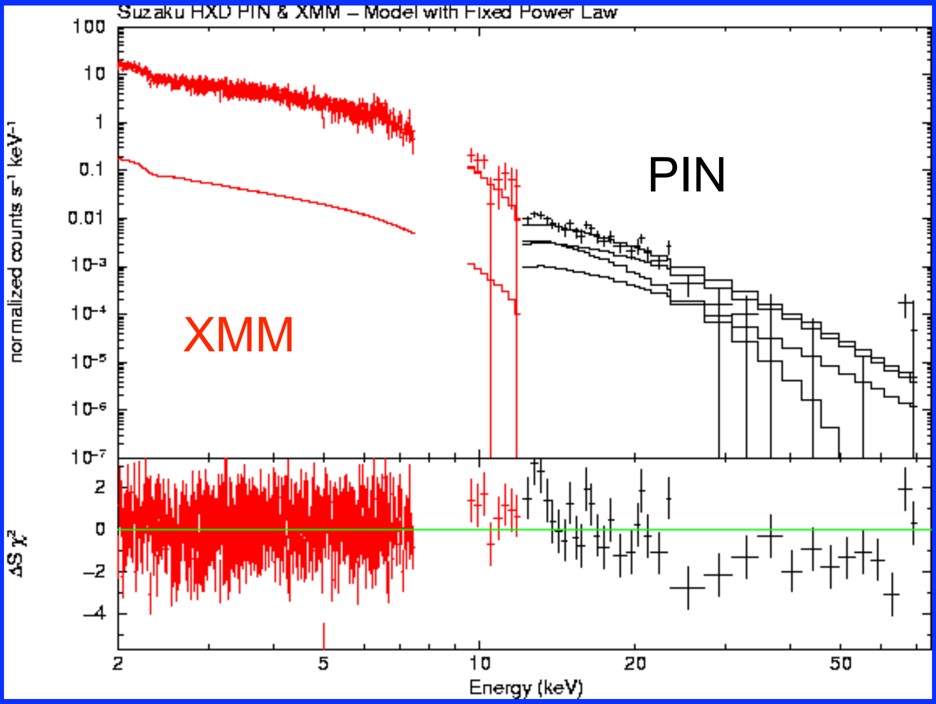


XMM Image from mosaic



Hard X-rays: PIN-XMM Results

- Detection of excess HXR
- Best-fit power-law $\Gamma = 3.2$, much steeper than radio
  $\rightarrow$ really thermal?
- Assuming power-law with
  $\Gamma = 2.1$ (radio)
  $F_X = 3.4 \times 10^{-12}$ ergs/cm^2/s
  12-70 keV
- Doesn't include systematic errors!!



Hard X-rays: PIN-XMM Results (Cont.)

Systematic Errors:

- NXB: ±5%
- CXB: ±20% (HXR flux, cosmic variance)
- XMM/PIN calibration: ±25%

→ $F_X < 7.6 \times 10^{-12}$ ergs/cm^2/s 12-70 keV

PIN+XIS analysis

$F_X < 9.4 \times 10^{-12}$ ergs/cm^2/s 12-70 keV

BeppoSAX PDS

$F_X < 9.3 \times 10^{-12}$ ergs/cm^2/s 12-70 keV

(Nevalainen et al. 2004)

Lower Limit on Magnetic Field

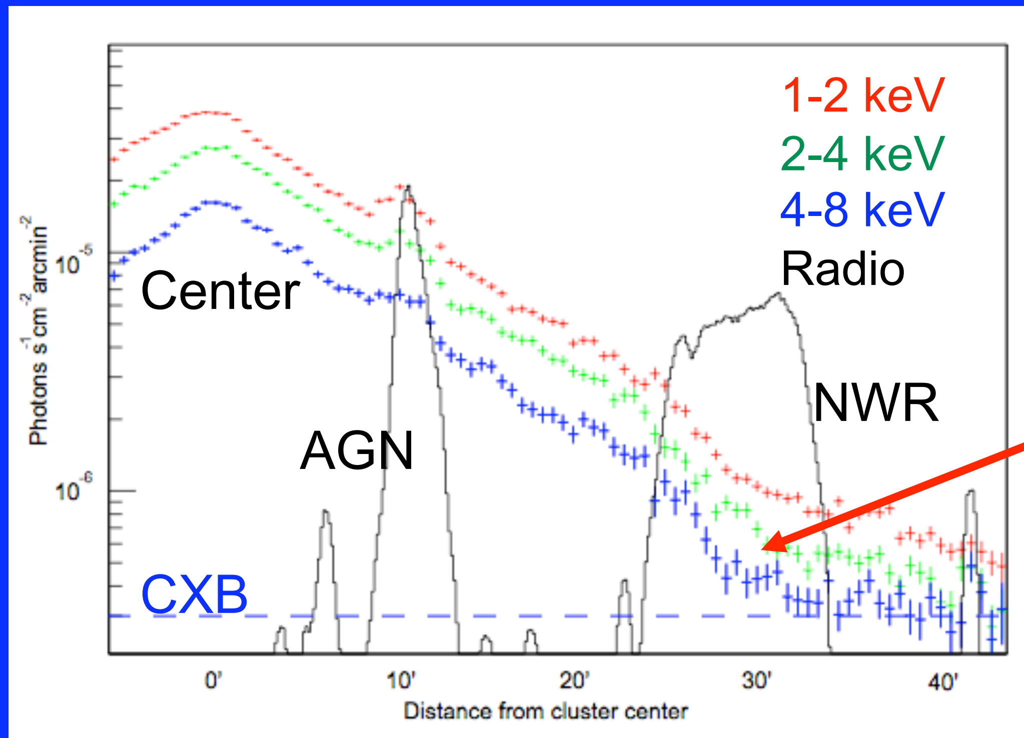
- Radio ∝ (energy in relativistic electrons) x (magnetic energy density)
- IC ∝ (energy in relativistic electrons) x
  (CMB energy density)
- Detect both → E(rel. e) & B
- Upper limit on IC → upper limit on E(rel. e).
  → lower limit on B

  E(rel. e) < 9 x 10^{61} ergs

  B > 0.5 μG

Tighter Limit from XIS

XIS and Radio Surface Brightness



Hard X-rays

No evidence for excess hard X-rays in XIS image or spectrum on radio relic

Tighter Limit from XIS (Cont.)

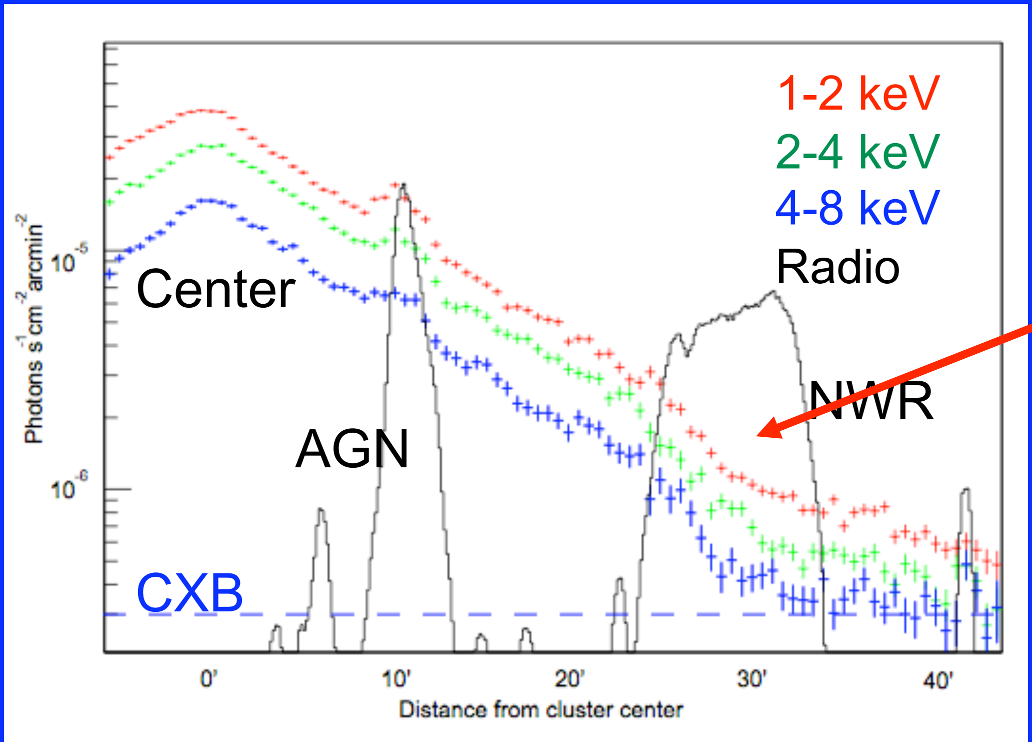
- Assume same spectral index at lower energies
- Assume XIS = thermal + IC
- Assume IC follows radio image
- Apply results to all of relic

→ $F_X < 2.6 \times 10^{-13}$ ergs/cm^2/s 10 - 40 keV

→ B > 2.2 μG, very strong magnetic field at projected radius of ~2 Mpc !!

Some previous evidence for a strong B in relic from Faraday rotation (Johnston-Hollitt 2004).

Evidence for Nonthermal Pressure of Relic



Soft X-rays: dip

X-ray/radio anticorrelation

Significant nonthermal pressure support? Typical, or just due to merger and/or relic?

Component	ICM	B	Rel-e
P (eV/cm^3)	~1.2	> 0.1	< 0.4

Ophiuchus Cluster

- One of hottest known clusters, $kT \approx 10$ kev
- Nearby $z = 0.028$
- Close to Galactic center in projection
  - Discovered in X-rays (Johnston et al. 1981)
- ASCA observation suggested merger?

  (Watanabe et al. 2001)

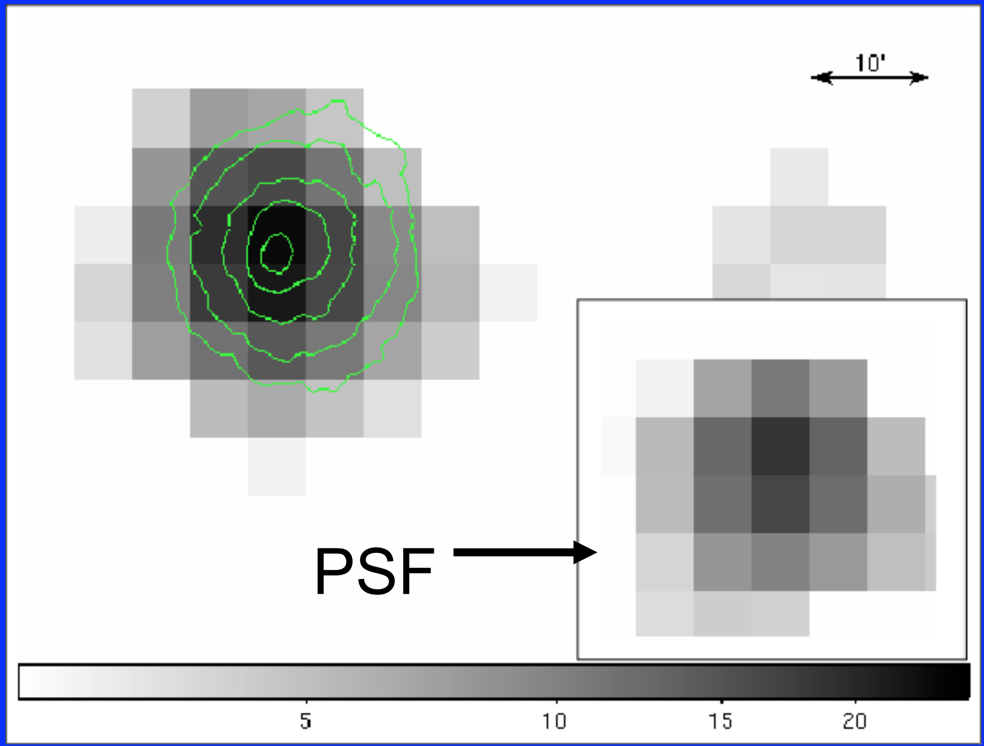
Ophiuchus: INTEGRAL IC Detection

- Long exposure with INTEGRAL (~3 Msec)

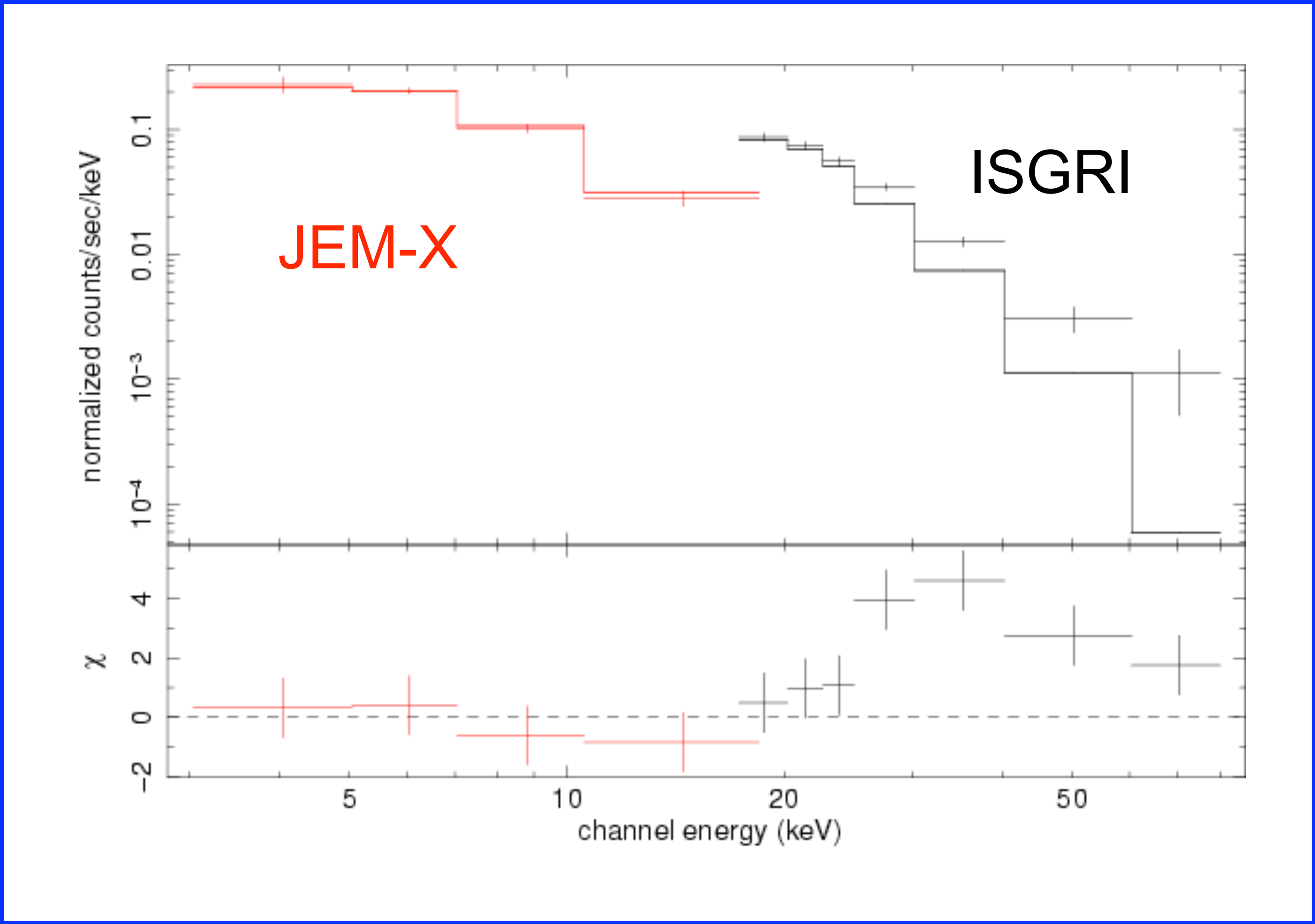
  (Eckert et al. 2008)

- Detected extended hard excess with IBIS/ ISGRI

  (coded mask)



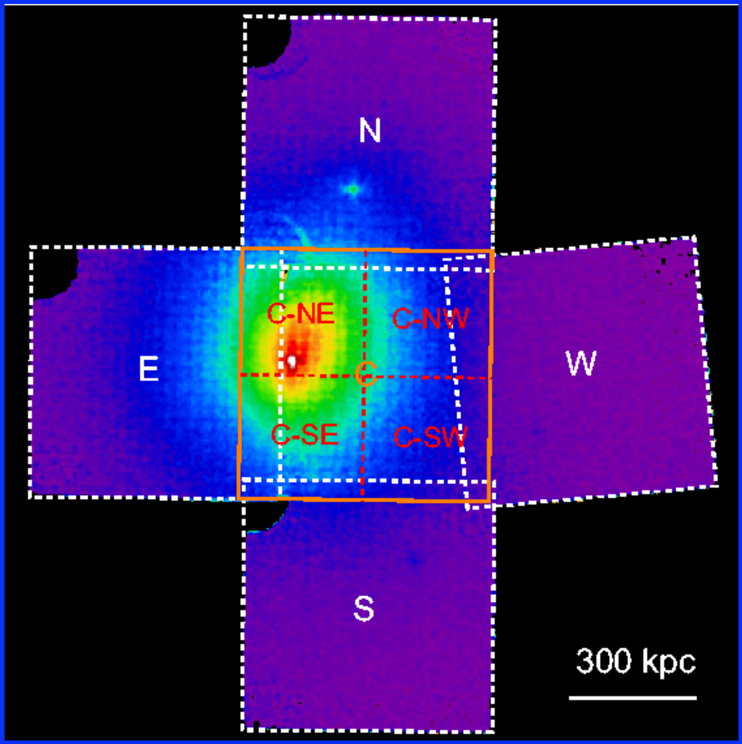
Best fit vs. 1 Temperature Model



$F_X = 1.0 \times 10^{-11}$ ergs/cm^2/s, 20-60 keV

Ophiuchus: Suzaku Observations

- 5 observation mosaic
- 105 ksec total
- 2007 March 21-24



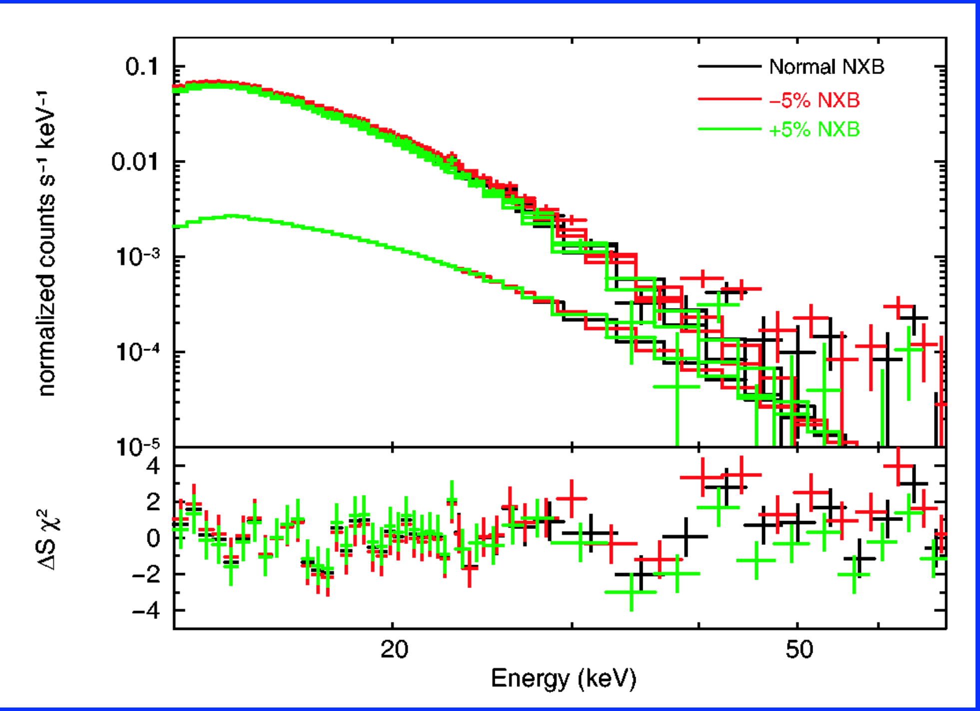
Ophiuchus: Suzaku Results

- No hard X-ray excess

$F_X < 3.2 \times 10^{-11}$ ergs/cm^2/s, 20-60 keV

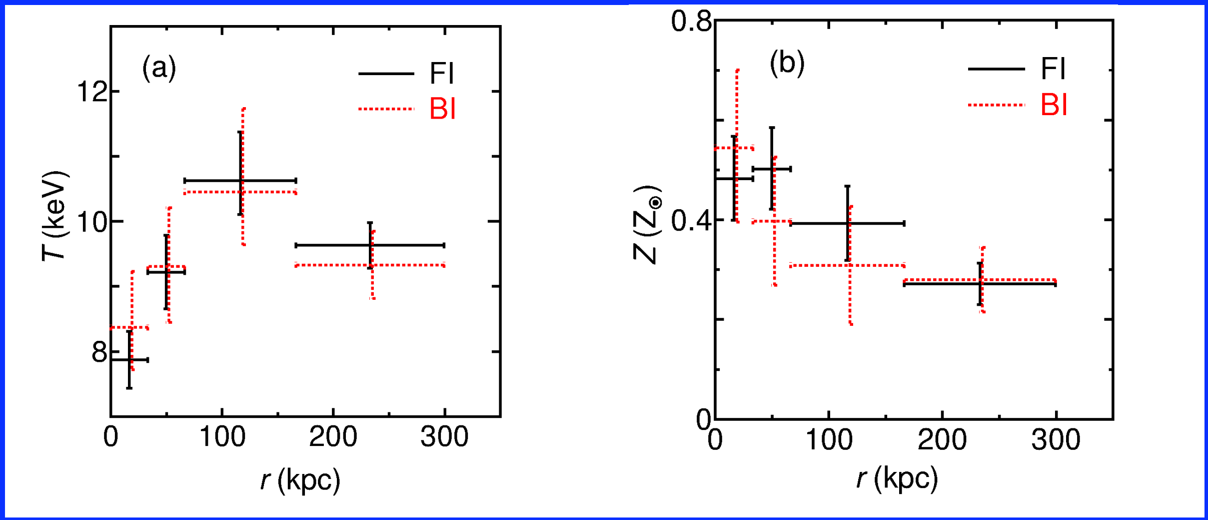
Consistent with INTEGRAL

T higher than assumed by Eckert et al.?



Ophiuchus: Suzaku Results

- Cluster is regular, no nonradial density or temperature structure
- Cluster has cool core with abundance gradient



Ophiuchus: Suzaku Results

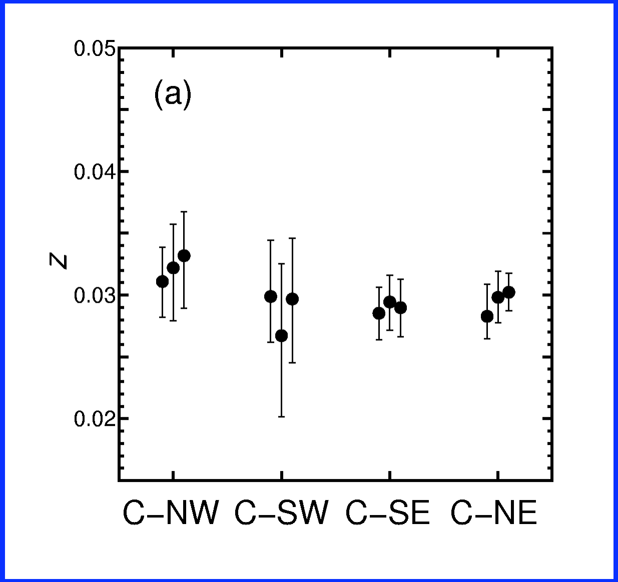
- No large velocity shear (<3000 km/s)

Not a merging cluster?

(or merger along line of sight?)

No radio halo or relic

What is the source of hard X-rays?



Conclusions

- Coma (Nakazawa et al. 2008)
  - Upper limit on IC, below BeppoSAX & RXTE detections
  - Hard excess probably thermal
- A3667 (Wik et al. 2008)
  - ICM extends out to ≈ 2.6 Mpc ≈ virial radius
  - PIN has hard excess, but may be thermal, and < systematic uncertainty
    - $F_X < 7.8 \times 10^{-12}$ ergs/cm^2/s 12-70 keV
    - E(rel. e) < 9×10^{61} ergs
    - B > 0.5 μG
  - No IC in XIS image or spectra
    - $F_X < 2.6 \times 10^{-13}$ ergs/cm^2/s 10 - 40 keV
    - B > 2.2 μG, very strong B at 2 Mpc
  - Significant nonthermal pressure support in radio relic?
- Ophiuchus (Fujita et al. 2008)
  - Not a merging cluster – source of hard X-rays?